THE SHM HYDROGEN ATOMIC CLOCK FOR SPACE APPLICATIONS

DEVELOPMENT AND TEST OF THE PEM PHYSICS PACKAGE

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Abstract

A compact Space-borne active Hydrogen Maser (SHM) frequency standard is being developed by the Observatory of Neuchâtel under the Swiss PRODEX program of ESA. The SHM instrument will be flown on the Radioastron (RA) mission in 2000 to be used as the reference clock for orbital Very Long Baseline Interferometry (VLBI) and for the red-shift experiment CRONOS.

The SHM design is based on a miniature sapphire loaded microwave cavity which makes possible an active hydrogen maser with a 1.7 liter storage volume for atomic hydrogen within a 50 kg space qualified instrument.

A preliminary measurement of the SHM instrument frequency stability using breadboard electronics has yielded an Allan deviation of $\sigma_y(1000s) = 3\times10^{-15}$ *which is already close to the* $\sigma_y(1000s) < 1.5\times10^{-15}$ *instrument specification. An extensive program for the design verification by test & analysis of the PEM-PP was performed in 1997 and is now near completion.*

Potential space applications of a compact active hydrogen maser instrument include scientific experiments related to relativity, precise ranging and navigation, time dissemination and synchronization. Present plans are to push miniaturization even further with the development of a 35 kg active hydrogen MAser for Navigation (MAN) for GNSS applications.

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THE SHM INSTRUMENT

INTRODUCTION

The Observatory of Neuchâtel (ON) is developing a compact hydrogen maser for space applications, based on a miniature sapphire loaded microwave cavity. The hydrogen maser is a high performance frequency standard capable of a frequency stability of about 1×10^{-15} over averaging intervals from 1,000s to 10,000 s. If used as a clock, this is equivalent to a time stability of 0.7 ps over a 1,000 s time interval or 7 ps over a 10,000 s time interval. The SHM instrument was developed to fly on the international Radioastron (RA) orbital VLBI mission to be used as the alternate master clock. The SHM instrument was also designed to be used for an accurate measurement of the red-shift effect, i.e. the time dilatation due to the gravitational field. This is the purpose of the CRONOS experiment proposed by ON and sponsored by the Swiss PRODEX program of ESA. The RA mission and the CRONOS experiment were reported previously in references [1], [2], [6].

DEVELOPMENT STEPS

The SHM compact hydrogen maser frequency standard is based on a Miniature sapphire loaded Microwave Cavity (MMC) designed by ON in 1993 under a first ESTEC contract for the development of the SHM instrument [3], [5]. The development was continued up to now through several design and breadboarding steps that are reported in references [3] to [6]. The design of the SHM Physics Package (PP) makes use of several sophisticated technologies and many problems had to be overcome in the course of development. Technologies and development activities worth to be mentioned are : the optimization of the atomic storage volume in the sapphire loaded microwave cavity, the manufacturing of a very large sapphire cylinder, the diffusion bonding of sapphire to titanium, the vapor deposition plating of the internal surface of a titanium cylinder, the machining by electro-erosion of the main titanium structural part, the teflon coating of the composite titanium-sapphire atomic storage bulb, the development of a special process of the magnetic shields that optimizes the permeability in zero field, the evaluation of the pumping speed, capacity and brittleness of the hydrogen getters.

PEM-PP DESIGN VERIFICATION PROGRAM

The last major step of development was the manufacturing and the first integration of the PEM-PP. The prototype Physics Package was manufactured during the first half of 1996 and first integrated in October and November 1996. The first atomic signal from the fully integrated PEM-PP was obtained in December 1996.

A first evaluation of the PEM-PP was performed in January and February 1997. The atomic quality factor, the atomic signal power and the short-term frequency stability characteristics of the PEM-PP were verified experimentally. The PEM-PP was then disassembled and several design modifications were implemented during the first half of 1997. These modifications were known to be necessary but had been postponed in order to allow for a quick first integration and evaluation.

A detailed structural analysis of the PEM design was performed in 1997 by CSEM, a Swiss engineering company. For the purpose of analysis CSEM has developed a finite elements structural model of the SHM

instrument with more than 7,000 nodes. The detailed structural analysis included : static loading, random vibration analysis, shock analysis, load safety margins, buckling analysis, thermal stress analysis and fracture control analysis. The main conclusion of CSEM's engineering analysis is that the PEM design is compliant with the Radioastron requirements without modifications. Several design improvements to the mechanical design were also suggested by CSEM.

The Reduced Microwave Cavity & magnetic Shields Assembly (RMCSA), the heart of the Physics Package which contains the atomic hydrogen storage bulb, is also the most complex part of the Physics Package from the structural point of view. A spare RMCSA unit, identical to the one used in the PEM-PP, was tested successfully for shocks (40 g shock response spectrum) and for random vibration (7 g rms) to the Radioastron qualification levels on May 14-15 1997. The same unit was also tested for random vibration to the GPS clocks qualification levels (14 g rms) on September 25 1997 in preparation to future applications of the SHM design for GNSS.

The Preliminary Design Review (PDR) of the PEM SHM instrument was opened on October 29 1997 under the technical supervision of ESA. The reviewed material include the design definition documents, the design verification by inspection and analysis, and the design verification by test on the PEM-PP. The PEM-PP PDR is scheduled to be closed at the end of 1997.

PERSPECTIVES FOR FUTURE DEVELOPMENT

After the closure of the PEM-PP PDR, the next step will be to kick-off a contract for the development of a PEM SHM space compatible Electronics Package (EP).

On the basis of the existing breadboard electronics, the development of the space compatible PEM-EP is expected to take one year. The fully integrated and tested PEM SHM instrument will then be delivered to Astro Space Center in Moscow for the purpose of ground testing the Radioastron payload. In particular it is planned to perform a VLBI session on the ground using the actualRadioastron payload.

Another flight opportunity for the SHM instrument is the ACES atomic clocks experiment proposed by a team of French scientists for the early utilization of the International Space Station. The ACES experiment is yet to be officially endorsed by ESA and involves the demonstration in space of a cold atom cesium fountain and other atomic clocks [7], [8]. The ACES SHM design would be very close to the Radioastron design. The extra effort of development would concern mainly the adaptation of the instrument interfaces. A system study of the ACES Concept has already been performed by CNES for the Space Station Applications and Promotion Office of ESA [9], [10]. The study considers the SHM instrument as one of the necessary components of the ACES experiment.

Besides, a collaboration of ON with the Naval Research Laboratory (NRL) is in preparation for the joint development of a 35 kg active hydrogen MAser for Navigation (MAN). This new development will take advantage of the technologies already developed for the SHM instrument in the course of the Radioastron & CRONOS project. It is foreseen to test the MAN maser for navigation on an experimental basis as a Reserve Auxiliary Payload (RAP) on a Block IIF GPS satellite.

SHM-RA Instrument Design

Condensed Specification

- long-term drift : $< 3\times10^{-12}$ year^{-1}
- output levels : 0.4 V_{rms} in 50 Ω
- operating temp. range: 10°C to 35°C
- thermal sensitivity: $\leq 3\times10^{-15}$ °C^{-1}
- magnetic field range: ± 1 gauss
- magnetic sensitivity: $\leq 2\times10^{-14}$ G^{-1}

- DC input voltage: 22 to 50 V
- power consumption: < 70W
- largest diameter (horizontal) 460 mm
- full height (vertical) 600 mm
- mass 50 kg
- mission lifetime > 3 years

τ [s]	Allan deviation
1	$< 1.5 \times 10^{-13}$
10	$< 2.1 \times 10^{-14}$
100	$< 5.1 \times 10^{-15}$
1'000	$< 2.1 \times 10^{-15}$
10'000	$< 1.5 \times 10^{-15}$

Table 1
Frequency Stability

	14.71 MHz output	5 MHz output
f [Hz]	*L* (f) [dBc]	*L* (f) [dBc]
1	< -100	< -110
10	< -122	< -132
100	< -132	< -143
1'000	< -141	< -151
10'000	< -145	< -155

Table 2
Phase Noise

Maser Physics Design

The heart of the PP design concept is the sapphire loaded MMC. The internal volume of the MMC is 4.4 liters. This is to be compared with the 20 liters of a conventional circular microwave cavity tuned to the hydrogen hyperfine frequency. The storage volume for hydrogen is 1.7 liter which is comparable to a conventional design based on a full size cavity. It is basically the size reduction of the microwave cavity that has made possible the realization of a 50 kg SHM instrument. The sapphire cylinder of the MMC has both a microwave function, the dielectric loading of the cavity, and a maser physics function since, together with the bonded titanium covers, it also constitutes the hydrogen storage bulb.

State selection is performed by a conventional quadrupole magnetic state selector. The dissociator is a small fused quartz bulb. The solid-state hydrogen supply is stored in a container filled with 90 g of hydride material Hydralloy C20. Magnetic shielding is performed by a set of four 0.5 mm magnetic shields around the MMC and by a fifth 0.5 mm magnetic shield that surrounds the whole instrument.

There are two vacuum systems : the hydrogen vacuum enclosure and the thermal vacuum enclosure. Each enclosure is pumped by a set of getters and by a set of two 2 l/s ion pumps. For each enclosure, one ion pumps would be sufficient. The second pump is there for redundancy. The sealed part of the PP is closed by an aluminum bell jar that closes the thermal vacuum enclosure.

MECHANICAL DESIGN

The SHM instrument is designed to pass the Radioastron qualification requirements for shocks (40g) and random vibration (7 g rms).

THERMAL DESIGN

In orbit the instrument is covered by a MLI thermal insulation blanket. All thermal exchanges are performed by conduction to a dedicated thermally controlled base plate which is part of the spacecraft.

The temperature of the MMC is stabilized by three concentric pairs of electronic thermal control loops. The first layer of thermal control is the MMC itself, the second layer is the c-field thermal shield and the third layer is the intermediate thermal shield. All these elements are inside the thermal vacuum system. The vacuum bell jar is not thermally controlled and follows passively the base plate temperature.

ELECTRONICS DESIGN

The ACT (Automatic Cavity Tuning) system is the most important performance critical element of the electronics package. Because of the cavity pulling effect, and given the -65 kHz /°C thermal sensitivity of the MMC, it is not possible to achieve the frequency stability and the thermal coefficient specified at the instrument level with only a thermal frequency control of the MMC. The function of the ACT system is to complement the thermal frequency control of the MMC by a varactor electronics frequency control.

EVALUATION OF THE PEM PHYSICS PACKAGE

MICROWAVE CAVITY

The measured loaded quality factor of the MMC is 34,000. The thermal coefficient of the TE_{011} mode is minus 65 kHz/°C.

ATOMIC QUALITY FACTOR

The operating atomic quality factor at -105 dBm of atomic signal output is 1.7×10^9.

THERMAL CONTROL

The thermal stability of the MMC is such that an Allan deviation of $\sigma_y(1{,}000s) = 2.2 \times 10^{-14}$ is achieved without ACT, i.e. with only a thermal frequency control of the MMC. This is equivalent to a thermal stability of $\sigma_T(1{,}000s) = 26\mu{}^\circ C$ at the MMC level. Only 7.5 W of electrical power is necessary for the thermal control of the physics package in air with the MMC at 47 °C, an ambient temperature of 20 °C,

and with no thermal insulation of the thermal vacuum bell jar. In vacuum, with the physics package protected by its MLI blanket, the power consumption will be even smaller.

BREADBOARD ACT

The breadboard ACT is still in development and does not reach yet the specified thermal sensitivity. Without ACT, i.e. with only a thermal frequency control of the MMC, the measured thermal coefficient is $5\times 10^{-12}\,{}^{\circ}C^{-1}$. The thermal coefficient improves to $3\times 10^{-14}\,{}^{\circ}C^{-1}$ when the breadboard ACT is put into operation. Note that, in this experiment, the breadboard electronics were maintained at a constant room temperature while the temperature of the PP was varied. Therefore long cables linking the PP to the EP were involved. A new iteration of the ACT breadboard electronics, better integrated and more compact, is in preparation and is expected to improve the thermal sensitivity up to the specified level.

Regarding the frequency stability specification, on the other hand, the Allan deviation measured with the breadboard ACT is $\sigma_y(1'000s) = 3\times 10^{-15}$. This is already quite close to the specification.

MAGNETIC SHIELDING

The shielding factor measured with only the four cavity shields is 20,000. A global shielding factor of 200,000 is expected with 5 shields.

GETTERS & ION PUMPS

It was verified that the vacuum system has an autonomy of at least 10 days without electrical power to the ion pumps (getters only). This requirement is specific to the Radioastron mission and is motivated by the fact that during several critical phases of the payload integration, connection of the instruments to a power supply is not allowed. Regarding the operational lifetime of the vacuum system, on the other hand, it is worth mentioning that the vacuum getters are known to become brittle after absorbing a large quantity of hydrogen. In order to avoid this drawback, the supply of hydrogen getters was designed in such a way that only 10% of their nominal capacity for hydrogen is used during the operational lifetime.

CONCLUSION

The evaluation of the PEM SHM-PP reported in this paper is still in progress but most of the important conclusions have been drawn already. Most of the design parameters have been measured and analyzed and have been shown to be compliant with the specifications. In particular the maser physics parameters, i.e. atomic quality factor and short-term stability, have been verified and the detailed structural analysis performed by CSEM has shown that the design is compliant with the random vibration and shock requirements of Radioastron. The shock and random vibration tests of the spare RMCSA assembly have validated the finite elements model of CSEM and confirmed the conclusions of the strutural analysis.

On the other hand, the breadboard electronics package is still in development and does not reach yet all the performance goals set by the instrument specifications. A new iteration of the breadboard ACT is in preparation and is expected to comply with the thermal sensitivity and frequency stability requirements.

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